New transportable atom sensors and their applications to space experiments

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Source Atomiques Cohérentes et Interférométrie Atomique

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Atom Interferometry: basic principle
 Atom Inertial Base (gyro + accelerometer)
 Coherent Atom Sensors
 I.C.E.: Transportable Sensor with atom laser
 The next 0-g Campaign
Atom accelerometer

- Based on Raman pulses atom optics
  \[ \pi/2 - \pi - \pi/2 \] (Kasevich & Chu 1991): interferometer
  \[ \pi/2 \]: create a superposition of 2 different velocities: beam splitter
  \[ \pi \]: exchanges velocities: mirror

- We use an (optical) ruler to precisely measure the (atomic) test mass position
  \[ \text{Similar to falling corner cube gravimeter (FG5)} \]
  \[ \text{FG 5: Laser phase is read by optical interferometry} \]
  \[ \text{Atom sensor: Laser phase is read by atom interferometry.} \]

- An Atom Interferometer “reads” the position of an atom proof mass using some kind of “laser telemetry”
  \[ \text{Velocity measurement improves with time} \]
  \[ \text{Acceleration measurement improves with time} \]
  \[ \text{Absolute accuracy} \]
  \[ \text{Example: watt balance for kg definition} \]
  \[ \text{Performances Similar to best sensors} \]
  \[ \text{Extension to low frequency} \]

\[ \cos(kx + \Phi_0) \]
Atom Gyrometer

- 3 Raman pulses separated in time
  - Atoms with an initial velocity perpendicular to lasers
  - Sensitivity to rotation = coriolis acceleration

$$\Delta \Omega_{\text{min}} = \frac{\Delta a_{\text{cor.}}}{2 \sqrt{v_y}} = \frac{\kappa}{m} \frac{\vec{a}}{L v_y T V N}$$
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Typical Atom Sensor Architecture

- Light Source
- Fibre optics
- Control Real-time
- Atomic Physics Chamber
  Robust, flexible
- Measurement Camera, accelerometer
- Computing Man-machine interface
Cold Atom Inertial Base (SYRTE)

Maximum interaction time: 80 ms
3 rotation axes, 2 acceleration axes
Cycling frequency 2Hz
Sensitivity (10^6 at):
- gyroscope: $3.5 \times 10^{-7} \text{ rad.s}^{-1}.\text{Hz}^{-1/2}$
- accelerometer: $8 \times 10^{-7} \text{ m.s}^{-2}.\text{Hz}^{-1/2}$

Magneto-Optical Traps
Launching velocity: 2.4 m.s^{-1}
Horizontal velocity: 0.33 m.s^{-1}

One pair of Raman lasers switched on 3 times

SEE FOLLOWING TALK ON GRAVIMETER
Ultimate limits for atom accelerometers?

<table>
<thead>
<tr>
<th>$T_c$ (s)</th>
<th>$2T$ (s)</th>
<th>Source 1 $\sigma_\Phi(T_c)$ (mrad)</th>
<th>Source 2 $\sigma_\Phi(T_c)$ (mrad)</th>
<th>Source 3 $\sigma_\Phi$ (mrad)</th>
<th>Best Source $\sigma_a(T_c)$ (m.s$^{-2}$) / shot</th>
<th>Best Source $\sigma_a(1s)$ (m.s$^{-2}$.Hz$^{-1/2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>0.1</td>
<td>1.2</td>
<td>3.5</td>
<td>2.2</td>
<td>$3 \times 10^{-8}$</td>
<td>$1.5 \times 10^{-8}$</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>22</td>
<td>8.8</td>
<td>4.6</td>
<td>$1.1 \times 10^{-9}$</td>
<td>$3.6 \times 10^{-9}$</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>55</td>
<td>20</td>
<td>10</td>
<td>$9.9 \times 10^{-11}$</td>
<td>$3.1 \times 10^{-10}$</td>
</tr>
<tr>
<td>15</td>
<td>10</td>
<td>110</td>
<td>37</td>
<td>19</td>
<td>$4.7 \times 10^{-11}$</td>
<td>$1.8 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

Table 1. Contribution of the 100 MHz source phase noise to the interferometric phase fluctuations ($\sigma_\Phi$) and to the acceleration sensitivity ($\sigma_a$). The calculation has been performed for a $^{87}$Rb interferometer, for each of the three different sources assuming pulse duration $\tau_R=10$ $\mu$s. $T_C$ is the cycle time for measurements, $2T$ is the total interrogation time. (Source 1: Premium; Source 2: BVA; Source 3: PHARAO)

 Nyman et al., cond-mat/0605057 and App. Phys. B 84(4) 673

Metrology

- Accelerometer precision of a few $10^{-10}$ m/s$^2$ per shot (5 s interrogation time)
- Limit due to Raman-laser phase noise
  - Noise comes from quartz oscillator

It is possible to go to a few seconds of interrogation time

- Well suited for space applications
- Best atom source?
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Why Coherent Source

- Ultra cold
  - Longer interrogation
  - Better signal to noise
    - but lower flux!

- Atom Laser: space applications
  - Small source
  - «New» Physics
    - Correlation, condensed matter

Le Coq et al., App. Phys. B 84(4)
Gravitational “resonator” for BEC

2 resonance condition
- Bragg (or Raman) resonance
- Oscillation resonance

\[ T_0 = \frac{4\hbar k}{mg} \]

Impens, Bouyer, Bordé , App. Phys. B 84(4)
Heisenberg-limited spectroscopy with degenerate Bose-Einstein gases

P. Bouyer and M. A. Kasevich
Department of Physics, Stanford University, Stanford, California 94035
(Received 14 March 1997)

We propose an experiment that exploits the quantum interference between two noninteracting ensembles of spatially degenerate Bose-Einstein atoms to measure phase shifts of atomic coherences at the Heisenberg limit.

[S1050-2947(97)50207-1]

PACS number(s): 03.75.Dg, 03.75.Fi

- Heisenberg limited with number states
- Compensates low atom number S/ N=10^6
- Integrated interferometers
  - BEC on chips
- «active» interferometers
  - Matter wave amplification
A Guided Atom Laser

- So far, RF outcoupled lasers from a magnetic trap
- Once atom lasers are extracted, they are subjected to gravity
- $\lambda$ becomes quickly very small

- BEC in hybrid (magnetic+optical) trap
  - Focused Nd:YAG laser (red detuned: 1064 nm)
  - Anisotrop: 2.5 Hz x 360 Hz ($z_R = 2.7$ mm)
  - Waist position chosen with translational stage
  - It is possible to use RF outcoupling
- RF extracted matter wave is guided in the optical trap
- Large de Broglie wavelength (1 µm)

W. Guerin et al., cond-mat/0607438
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Interferometry with Coherent Sources for Applications in Space

THE PROJECT

The objective of ICE is to produce an accelerometer for space with coherent atomic source. It uses a mixture of Bose-Einstein condensates with 2 species of atoms (Rb and K).

The major objective for 2007 is to carry out a first μg campaign, in parabolic flight for example, to test the various components together and to carry out a first comparison of accelerations measured by the 2 atomic species.
ICE : Strategy

- Use optical traps for “atom cavity”
- Optical fields easily switchable
  - No stray fields, only “diffusive effects”
  - Precision knowledge on position, velocity …

Compact BEC source:
  - Crucial: efficient loading scheme into the optical trap
  - Need powerfull laser
- Box superstructure
- Damped (foam filled)
- Grooves for adding optics anywhere in the volume
- Breadboard (low vibration)

- Suspend vacuum chamber with ropes, slings, chains
- Adjust tension with turnbuckles

2×10^8 at. in <5s
I. C. E. : Cubes (with atoms)

- Box superstructure
- Damped (foam filled)
- Grooves for adding optics anywhere in the volume
- Breadboard (low vibration)

2x10^8 at. in <5s

87Rb MOT, 10/02/2006

- Suspend vacuum chamber with ropes, slings, chains
- Adjust tension with turnbuckles
Optical Trapping with telecom lasers

- Using High power telecom laser to trap and manipulate the atoms.
- First trapping signal observed

- Transportability tested during lab moving
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I.C.E.: 0-g tests

Env. 10 mg max = 1s interrogation

Performances: $10^{-10}$ m.s$^{-2}$ Hz$^{-1/2}$

100 measures $\Rightarrow 10^{-11}$ m.s$^{-2}$

Need special isolation platform
I.C.E. : 0-g tests

- “Benchtest” experiment for testing atom manipulation with laser technology.
- “flight” ready for March 26th.
- No Coherent Atoms yet
Atom Interferometry: basic principle

Atom Inertial Base (gyro + accelerometer)

Coherent Atom Sensors

I.C.E. : Transportable Sensor with atom laser

The next 0-g Campaign
Post-doctoral position available. See www.atomoptic.fr